

Surficial Geologic Maps and Geologic Hazards of the Green Valley – Sahuarita Area, Pima County, Arizona

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Digital Geologic Map 3

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Includes 21 pages of text and 2 color geologic maps covering the Esperanza Mill, Green Valley, Sahuarita, and Twin Buttes quadrangles; also available on CD as Adobe PDF file

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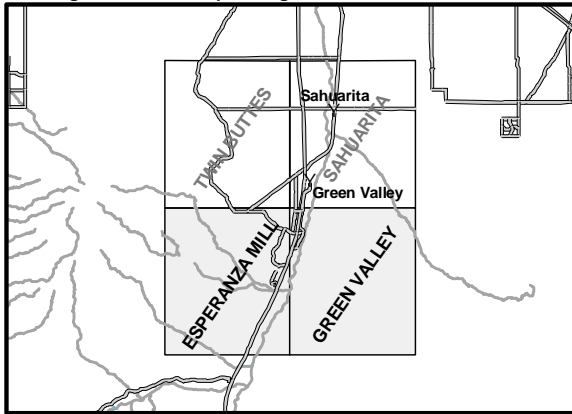
Introduction

This report and accompanying maps describe the surficial geology, geomorphology, and geologic hazards of the rapidly developing Green Valley – Sahuarita area on the southern fringe of the Tucson metropolitan area. The mapping covers the Esperanza Mill, Green Valley, Sahuarita, and Twin Buttes 7 1/2' quadrangles (Figure 1). Most of the area is in unincorporated Pima County, but it includes the small but rapidly growing Town of Sahuarita. The whole map area is within the drainage basin of the Santa Cruz River, a major, north-flowing regional drainage that roughly bisects the four quadrangles. These maps cover most of the Santa Cruz Valley (this area can also be considered the southern part of the Tucson basin) between the Santa Rita Mountains on the east to the Sierrita Mountains on the west.

There are several potentially conflicting land use issues in the area covered by these maps. It encompasses the southern fringe of the Tucson metropolitan area, which is experiencing rapid development and population growth. The western part of the map area includes several large open-pit copper mines that have been active for several decades. Much of the eastern part of map area is within the Santa Rita Experimental Range and Wildlife Area, a government-owned preserve that is undeveloped and will remain that way for the foreseeable future. Intense urban development has occurred and is continuing in the Green Valley area. Major developments have been proposed for the Canoa Ranch area along the Santa Cruz River. Rapid development is beginning in Sahuarita, which is on the suburban fringe of the Tucson metropolitan area. This report is intended to enhance our understanding of the surficial geology of the Green Valley – Sahuarita area and to aid in assessing and understanding geologic hazards in this area. This new mapping complements previously published mapping that focused on the bedrock in the area (Drewes, 1971; Cooper, 1973).

This surficial geologic mapping in the Green Valley – Sahuarita area is part of continuing efforts by the AZGS to map the geology of the Phoenix – Tucson urban corridor. It builds on and complements previous surficial geologic mapping efforts in the Tucson area (McKittrick, 1988; Jackson, 1989; Jackson, 1990; Demsey and others, 1993; Klawon and others, 1999; Pearthree and Biggs, 1999). The report is organized into a brief introduction and explanation of mapping methods, unit descriptions, a summary of the geologic and geomorphic framework of the area, and a discussion of geologic hazards. Ray Harris, Tim Orr and Steve Richard assisted with map digitization and preparing the map layouts and provided quality control for the map compilation. Ray Harris contributed to the section on ground water withdrawal and subsidence. Mapping was conducted as part of the STATEMAP Program of the U.S. Geological Survey, contract #99HQAG0171, and was supported by the Arizona Geological Survey and the U.S. Geological Survey National Cooperative Mapping Program.

MAP OF THE GREEN VALLEY - SAHUARITA AREA
 Showing the location of quadrangles on Plate 2



INDEX MAP OF ARIZONA
 Showing location of Pima
 County and map area

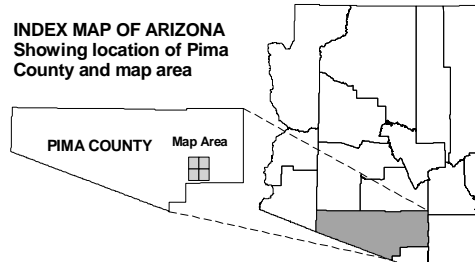


Figure 1. Location of the four quadrangles covered by this report, on the south side of the Tucson basin.

Climate. Several weather stations in the Tucson basin that have operated during intervals over the past century provide climatological data for the study area. The current Tucson Weather Service Office at Tucson International Airport (WSO, just north of the Sahuarita quadrangle) has records from 1948 to the present and the weather station maintained at the Santa Rita Experimental Range Headquarters (ERH, just east of the Green Valley quadrangle) has records from 1950 to present. Stations at Sahuarita (1956-1972) and Helvetia (1916-1950) were maintained for parts of the 20th century. Throughout this region, most of the annual precipitation (50-60%) falls during the summer monsoon from June to September. Late summer rainfall occurs as heavy thunderstorms when moist air sweeps northwards from the Gulf of California and the Gulf of Mexico. Occasional intense late summer to early fall precipitation occurs in this region as a result of incursions of moist air derived from dissipating tropical storms in the Pacific Ocean. The largest recorded flood on the Santa Cruz River, which occurred in early October, 1983, was generated by moisture from a tropical storm. Winter precipitation generally is caused by cyclonic storms originating in the Pacific. It is usually less intense and may be more prolonged, and therefore infiltrates into the soil more deeply than summer rainfall (summarized from Sellers and Hill, 1974). Freezing temperatures are common during most winters, but snow is uncommon and not persistent.

Climate records from the WSO at about 2500 ft asl and the ERH at 4000 ft asl illustrate the pronounced precipitation and temperature gradients across the map area (Western Regional Climate Center, 2000). Average annual precipitation for the WSO is 11.6 in. and the average maximum temperature is 82.5° F, with an average high temperature of 99.1° F in July and 64.7° F in January. This approximates the relatively warm and dry climate in the lower elevation (northern) part of the map area. The southeastern part of the map area is substantially wetter and somewhat cooler. Average annual precipitation of 22.2 in. at the ERH is nearly double the annual precipitation in the middle of the Tucson basin. The average annual maximum temperature at the ERH is 76.4° F, with average high temperatures of 91.6° F in July and 60.2° F in January. The average annual precipitation for ERH is probably a maximum for the map area because of its proximity to the base of the Santa Rita Mountains.

Methodology

The surficial geology of the project area was mapped using black-and-white aerial photographs taken in 1998 and color aerial photos taken in 1979. Unit boundaries were spot-checked in the field, and mapping was supplemented by observations and descriptions of soils and stratigraphy. The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) evident on aerial photographs and in the field were used to differentiate their associated deposits by age. Surficial deposits of this quadrangle were then correlated with similar deposits in this region in order to roughly estimate their ages. Original mapping was done on aerial photos and compiled on 7 ½' quadrangle maps. The map compilations were then digitized and the final maps were generated from the digital data.

The physical characteristics of Quaternary alluvial surfaces (channels, alluvial fans, floodplains, stream terraces) were used to differentiate their associated deposits by age.

Alluvial surfaces of similar age have a distinctive appearance and soil characteristics because they have undergone similar post-depositional modifications. They are different from both younger and older surfaces. Terraces and alluvial fans that are less than a few thousand years old still retain clear evidence of the original depositional topography, such as of bars of gravel deposits, swales (troughlike depressions) where low flows passed between bars, and distributary channel networks, which are characteristic of active alluvial fans. Young alluvial surfaces have little rock varnish on surface clasts and have little soil development, and they are minimally dissected. Very old fan surfaces, in contrast, have been isolated from substantial fluvial deposition or reworking for hundreds of thousands of years. These surfaces are characterized by strongly developed soils with clay-rich argillic horizons and cemented calcium-carbonate horizons, well-developed tributary stream networks that are entrenched 1 to 10 m below the fan surface, and strongly developed varnish on surface rocks. The ages of alluvial surfaces in the southwestern United States may be roughly estimated based on these surface characteristics, especially soil development (Gile and others, 1981; Bull, 1991).

In this map, Quaternary surficial deposits are subdivided based on their source (axial valley stream and smaller tributary washes on piedmonts) and estimated age of deposits. Surface and soil characteristics were used to correlate alluvial deposits and to estimate their ages. Surface pits and exposures along cut banks were used to assess soil characteristics associated with deposits of different ages and from different sources. Soils and surfaces documented in the map area were generally correlated with soils and surfaces described in Quaternary mapping studies of adjacent areas conducted by Jackson (1989), Jackson (1990), Klawon and others (1999), Pearthree and Biggs (1999), and Pearthree and others (2000). These correlations were also used to estimate the ages of surficial deposits in the map area.

Map Unit Descriptions

Piedmont Alluvium

Quaternary and late Tertiary deposits cover the most of the piedmont areas east of the Sierrita Mountains and west of the Santa Rita Mountains. This alluvium was deposited primarily by larger streams that head in the mountains; smaller streams that head on the piedmont have eroded and reworked some of these deposits. Deposits range in age from modern to early Pleistocene or Pliocene. The lower margin of the piedmonts are defined by their intersection with stream terraces of the Santa Cruz River. Approximate age estimates for the various units are given in parentheses after the unit name. Abbreviations are ka, thousands of years before present, and Ma, millions of years before present. See Table 1 for general surface and soil characteristics of most of the piedmont units.

Qy₂ - Late Holocene alluvium (<~2 ka). Unit Qy₂ consists of channels, low terraces, and small alluvial fans composed of cobbles, sand, silt and boulders that have been recently deposited by modern drainages. In upper piedmont areas, channel sediment is generally sand, pebbles and cobbles, with some boulders; terraces typically are mantled with sand and finer sediment. On lower piedmont areas, young deposits consist predominantly of sand and silt, and some cobbles in channels. Channels generally are incised less than 1 m below adjacent terraces and fans, but locally incision may be as much as 2 m. Channel morphologies generally consist of a single-thread high flow channel or multi-threaded low flow channels with gravel bars adjacent to low flow channels. Downstream-branching distributary channel patterns are associated with the few young alluvial fans in the area. In these areas, channels typically are discontinuous, with small, well-defined channels alternating with broad expansion reach where channels are very small and poorly defined. Local relief varies from fairly smooth channel bottoms to the undulating bar-and-swale topography that is characteristic of coarser deposits. Terrace surfaces typically have planar surfaces, but small channels are also common on terraces. Soil development associated with Qy₂ deposits is minimal (see Table 1 for more soils information). Terrace and fan surfaces are brown, and on aerial photos they generally appear darker than surrounding areas, whereas sandy to gravelly channels appear light-colored on aerial photos. Vegetation density is variable. Channels typically have sparse, small vegetation. The densest vegetation in the map area is found along channel margins and on Qy₂ terraces along channels. Along the larger washes, tree species include mesquite, palo verde, and acacia; smaller bushes and grass may also be quite dense. Smaller washes typically have palo verde, mesquite, large creosote and other bushes along them.

Qy₁ - Holocene alluvium (0 to ~10 ka). Unit Qy₁ consists of low terraces found at scattered locations along incised drainages throughout the Sierrita piedmont. Qy₁ surfaces are slightly higher and less subject to inundation than adjacent Qy₂ surfaces. Surfaces are generally planar; local relief may be up to 1 m where gravel bars are present, but typically is much less. Qy₁ surfaces are less than 2 m above adjacent

active channels. Surfaces typically are sandy but locally have unvarnished open fine gravel lags. Qy₁ surfaces generally appear fairly dark on aerial photos, but where a gravel lag is present, surfaces are light colored. Channel patterns on alluvial fans are weakly integrated distributary (branching downstream) systems. Qy₁ terrace surfaces support mesquite and palo verde trees, and smaller bushes may be quite dense. Qy₁ fans support scattered trees along channels, but creosote and other small bushes are dominant. Qy₁ soils typically are weakly developed, with some soil structure but little clay and stage I to II calcium carbonate accumulation (see Machette, 1985, for description of stages of calcium carbonate accumulation in soils).

Qy – undifferentiated Holocene alluvium (0 to ~10 ka). This unit includes both Qy₂ and Qy₁ deposits. It is used on the Santa Rita piedmont. Qy consists of low terraces adjacent to drainages and more extensive young alluvial fans. Soil development consists of cambic horizons over weak to moderate (stage I to II) calcic horizons. This map unit includes units 3b and 4 of Pearthree and Calvo (1987).

Qly - Holocene to Late Pleistocene alluvium (0 to ~130 ka). Broadly rounded alluvial fan surfaces approximately 1 m above active channels composed of mixed alluvium of late Pleistocene and Holocene age. Drainage networks consist of a mix of distributary channel networks associated with larger drainages and tributary channels associated with smaller drainages that head on Qly surfaces. Qly areas are primarily covered by a thin veneer of Holocene fine-grained alluvium (unit Qy), but reddened Pleistocene alluvium (unit Ql and rarely, Qm) is exposed in patches on low ridges and in roads and cut banks of washes. The Holocene surfaces usually are light brown in color and soils have weak subangular blocky structure and minor carbonate accumulation. Qly fans support palo verde and mesquite trees along washes and low shrubs and grass in interfluvial areas. This unit is generally correlative with units 2d and 3a of Pearthree and Calvo (1987).

Ql - Late Pleistocene alluvium (~10 to 130 ka).

Ql₂ – latest Pleistocene member (~10 to 20 ka)

Ql₁ – late Pleistocene member (~75 to 130 ka)

Unit Ql consists of slightly to moderately dissected relict alluvial fans and terraces found on the upper, middle and lower piedmont. Moderately to well-developed, slightly to moderately incised tributary drainage networks are typical on Ql surfaces. Active channels are incised up to about 2 m below Ql surfaces, with incision typically increasing toward the mountain front. Ql fans and terraces are commonly lower in elevation than adjacent Qm and older surfaces, but the lower margins of Ql deposits lap out onto more dissected Qm surfaces in some places. Ql deposits consist of pebbles, cobbles, and finer-grained sediment. Ql surfaces commonly have loose, open lags of pebbles and cobbles; surface clasts exhibit weak rock varnish. Ql surfaces appear light orange to dark orange on color aerial photos, reflecting slight reddening of surface clasts and the surface soil horizon. Ql soils are moderately developed, with orange to reddish brown clay loam to light clay argillic horizons and stage II calcium carbonate accumulation. Ql₁ soils have more clay, redder surface horizons, and

generally more extensive drainage networks on them, reflecting their greater antiquity. Dominant forms of vegetation include grasses, small shrubs, mesquite, and palo verde. Unit Ql₂ is generally correlative with unit 2d and unit Ql₁ is correlative with unit 2c of Pearthree and Calvo (1987).

Qmy – Holocene to middle Pleistocene alluvium (0 to ~750 ka). Mixed Holocene and Pleistocene alluvium on the lowermost part of the Sierrita piedmont in the urbanized portion of Green Valley. Exposures of undisturbed surfaces in this area are rare. Deposits and alluvial surfaces are set relatively low in the landscape and are not deeply dissected. Thus, they are likely of Holocene and late Pleistocene age but may include some older deposits as well.

Qm - Middle Pleistocene alluvium (~130 to 750 ka). Unit Qm consists of moderately highly dissected relict alluvial fans and terraces with strong soil development found throughout the map area. Qm surfaces are drained by well-developed, moderately to deeply incised tributary channel networks; channels are typically several meters below adjacent Qm surfaces. Well-preserved, planar Qm surfaces are smooth with scattered pebble and cobble lags; surface color is reddish brown rock varnish on surface clasts is typically orange or dark brown. More eroded, rounded Qm surfaces are characterized by scattered cobble lags with moderate to strong varnish, broad ridge-like topography and some carbonate litter on the surface. Well-preserved Qm surfaces have a distinctive dark red color on color aerial photos, reflecting reddening of the surface soil and surface clasts. Soils typically contain reddened, clay argillic horizons, with obvious clay skins and subangular to angular blocky structure. Underlying soil carbonate development is typically stage III, with abundant carbonate through at least 1 m of the soil profile; indurated petrocalcic horizons are rare. Qm surfaces generally support grasses, bursage, cholla, and small shrubs. Unit Qm is correlative with unit 2b of Pearthree and Calvo (1987).

Qm_p - Middle Pleistocene alluvium over dissected pediment (~130 to 750 ka). This label is affixed to the units in the western half of the Twin Buttes quadrangle. The dissected pediment formed on granodiorite is exposed on the ridgecrests and in some washes, but is covered with a thin, continuous Qm alluvial deposit over the lower slopes.

Qo – Early Pleistocene alluvium (~1 to 2 Ma).

Qo₂ – Younger member.

Qo₁ – Older member.

Unit Qo consists of very old, high, dissected alluvial fan remnants with moderately well preserved fan surfaces and strong soil development. Qo deposits and fan surface remnants are scattered across the southern Sierrita piedmont, but are best preserved near the mountain front. In that area, there are two distinct levels of Qo deposits and surfaces, both of which have strongly developed soils and are high above the modern channels. Where this is the case, Qo is subdivided into older and younger members. Qo deposits and surfaces are extensive and exceptionally well preserved in the

southern part of the Madera Canyon fan complex in the southeastern part of the map area. Qo surfaces range from fairly smooth to broadly rounded. Qo deposits consist of cobbles, boulders, and sand and finer clasts. Stage III to IV calcic horizons are typical. Where surfaces are planar and well-preserved, red, heavy clay argillic horizons are typical. Qo surfaces are dominated by grass, small shrubs, and ocotillo. Qo surfaces record the highest levels of aggradation in the Tucson basin and the Santa Cruz Valley, and are probably correlative with other high, remnant surfaces found at various locations throughout southern Arizona (Menges and McFadden, 1981; Helmick, 1986). Unit Qo is correlative with unit 2a of Pearthree and Calvo (1987).

QTs - Early Pleistocene to Pliocene alluvium (~1 to 5 Ma). Unit QTs consists of very old, deeply dissected and highly eroded alluvial fan deposits. QTs surfaces are alternating eroded ridges and deep valleys, with ridgecrests typically 10 to 30 meters above adjacent active channels. The thickness of QTs deposits is not known. QTs surfaces are drained by deeply incised tributary channel networks. Even the highest surfaces atop QTs ridges are rounded, and original highest capping fan surfaces are not preserved. QTs deposits are dominated by gravel ranging from boulders to pebbles. Deposits are moderately indurated and are quite resistant to erosion because of the large clast size and carbonate cementation. Soils typically are dominated by carbonate accumulation, which is typically stage V (cemented petrocalcic horizons with laminar cap) on ridgecrests. Carbonate litter is common on ridgecrests and hillslopes. On aerial photos, QTs surfaces are gray to white. QTs surfaces support creosote, mesquite, palo verde, ocotillo, and cholla. QTs includes areas mapped as the middle Tertiary Helmet Funglomerate by Cooper (1973).

Axial Stream Deposits

Sediment deposited by the Santa Cruz River covers a north-south-trending strip through the central part of the map area. Surfaces consist of channels and young stream terraces that compose the geologic floodplain. Deposits are a mix of gravel and sand and finer material; they exhibit mixed lithologies reflecting the large drainage areas of these streams. Virtually all of the area covered by river deposits has been altered by intense agricultural and urban develop, so there is greater uncertainty regarding the locations of unit contacts than in piedmont areas.

Qycr - Modern river channel deposits (< 100 years). This unit consists of river channel deposits of the Santa Cruz River. They are composed primarily of sand and gravel. Along the Santa Cruz River, modern channels are typically entrenched several meters below adjacent young terraces. The current entrenched channel configuration began to evolve with the development of arroyos in the late 1800's, and continued to evolve through this century (Betancourt, 1990; Wood and others, 1999). Channels have variable widths, but modern channels in much of the map area are relatively

uniform within artificial dikes. Channels are extremely flood prone and are subject to deep, high velocity in moderate to large flow events. Banks along some portions of the Santa Cruz River have been protected with soil cement, but other reaches are unprotected and are subject to several lateral erosion during floods.

Qyr - Holocene floodplain and terrace deposits (<10 ka). The Qyr unit consists of floodplains and low terraces flanking the main channel system along the Santa Cruz River. Most Qyr areas along the Santa Cruz River are part of the active floodplain and may be inundated in large floods. Terrace surfaces are flat and uneroded, except immediately adjacent to channels. Qyr deposits consist of weakly to unconsolidated sand, silt, and clay. Soils are weakly developed, with some carbonate filaments and fine masses and weak soil structure in near surface horizons. Locally, Qyr surfaces may experience sheetflooding during large floods in areas where the main channel is not deeply entrenched, and as a result of flooding on local tributaries that debouch onto Qyr surfaces. Unprotected channel banks formed in Qyr deposits are very susceptible to lateral erosion.

Hillslope Deposits

Qc – Holocene and Pleistocene hillslope colluvium. Unit Qc consists of locally-derived deposits on moderately steep hillslopes in the Sierrita Mountains. Colluvium is very extensive in the mountains, but is mapped only where sufficiently thick and extensive as to obscure underlying bedrock. Deposits are very poorly sorted, ranging from clay to cobbles and boulders. Clasts typically are subangular to angular because they have not been transported very far. Bedding is weak and dips are quite steep, reflecting the steep depositional environment. Deposits are a few meters thick or less; thickest deposits are found at the bases of hillslopes. Some stable hillslopes are covered primarily with Pleistocene deposits, which are typically reddened and enriched in clay. Other more active hillslopes are covered with Holocene deposits, which have minimal soil development.

Miscellaneous units and symbols

R – undifferentiated bedrock

Qd – Disturbed. Areas that have been so profoundly disturbed by human activity as to completely obscure the preexisting natural surface. Much of the area within these quadrangles had been substantially disturbed by development. This unit label is used only in areas where there was no chance of evaluating the nature of the surface on the aerial photographs used in this study, which date to 1998. Includes mine excavations and tailings. Extent of area affected by mining as shown on 1998 aerial photos.

Surficial unit / age	Maximum Redness	Maximum % clay	Maximum % iron	Depth to carbonate (cm)	Maximum stage calcic horizon
Qy2 <4 ka	7.5 YR 4/3 brown	7	0.6	35	I or none
Qy1 4-10 ka	7.5 YR 3 /4 dark brown	4	0.5	25 - 60	II
Ql2 10-20 ka	5 YR 4/6 yellowish red	6	0.4	80 - 150	I
Ql1 75-130 ka	5 YR 4/6 yellowish red	22	0.6	140 – 200	I-III
Qm 200-500 ka	2.5 YR 3/6 dark red	31 - 44	1.0 – 1.3	65 - 140	II-IV
Qo 1-2 Ma	10 R 3/6 dark red	67	1.3	--	--

Table 1. Soil characteristics for selected surficial units in the Green Valley – Sahuarita area. This particular soils chronosequence was described on the Santa Rita piedmont in the Madera Canyon area (the southeastern part of the map area). The original source for this data is Pearthree and Calvo (1987).

Geologic/Geomorphic Framework

The Tucson metropolitan area is located along the eastern edge of the Sonoran Desert subprovince of the Basin and Range physiographic province. The Basin and Range province in Arizona is characterized by alluvial basins and intervening mountain ranges that formed as a result of normal faulting related to extension of the crust between about 30 and 6 Ma (Shafiqullah and others, 1980; Menges and Pearthree, 1989). The landscape of the Tucson area consists of alluvial basins between large, high mountain ranges to the east and small, low-lying mountain ranges to the west. The western part of the metropolitan area (Avra Valley and the west side of the Tucson Mountains) is typical of the undissected basins that are common throughout the Sonoran Desert subprovince. Mountain ranges are low and mountain fronts are deeply embayed, with few outlying bedrock knobs (inselbergs) that rise above the broad plains surrounding the mountain ranges. Upper piedmont areas typically are covered with Pleistocene deposits that are moderately dissected, but lower piedmont areas are undissected and covered by relatively fine-grained young deposits that grade downslope into axial valley deposits. The axial portions of valleys are typically occupied by unentrenched drainages with very broad floodplains. In stark contrast, the eastern, northern, and southern parts of the Tucson area have large, high mountain ranges and piedmont areas have been deeply dissected by

erosion. In these areas, erosion has dominated landscape evolution at least through the Quaternary. Major periods of aggradation have punctuated the long-term trend toward downcutting along the major streams and their tributaries.

The highest levels of alluvial deposits (unit QTs and Qo) in the Green Valley – Sahuarita area may have been graded approximately to the ancestral Santa Cruz River before it was significantly entrenched. They are probably approximately correlative with QT deposits mapped in the Catalina foothills on the north side of the Tucson basin (Klawon and others, 1999), Qo and QT deposits mapped in the Tucson Mountain foothills on the west side of the Tucson basin (Pearthree and Biggs, 1999), and other high remnant deposits throughout southeastern Arizona (Menges and McFadden, 1981). It is likely that in the late Pliocene to early Quaternary, the surfaces of the Sierrita and Santa Rita piedmonts were fairly planar, undissected piedmonts that graded downslope to the floodplain of the through-flowing ancestral Santa Cruz river system.

During the past one to two million years, the Santa Cruz River and its tributaries have downcut substantially into the Quaternary and Tertiary deposits of the Santa Cruz Valley. The high ridges and deep valleys characteristic of parts of the Sierrita piedmont and the high remnant fan surfaces of the Santa Rita piedmont attest to the amount of stream erosion that has occurred since the highest levels of alluvium were deposited. Episodes of downcutting of the Santa Cruz River caused erosion of the toes of alluvial fans on both sides of the valley, and resulted in much of the stream downcutting in the piedmonts east and west of the river. Streams that head in the Santa Rita and Sierrita mountains flow across the piedmonts and eventually join the Santa Cruz River. The lower ends of these streams are linked with the river, so if the Santa Cruz downcuts, the slopes of its tributary stream channels steepen and they tend to downcut as well. The ultimate cause of the Santa Cruz River downcutting is not certain. It may have occurred a delayed response of the integration of the Tucson basin streams into the larger regional drainage system, or it may have been driven by some broad regional upwarping of southeastern Arizona (Menges and Pearthree, 1989).

The fact that we observe suites of alluvial surfaces with similar characteristics and topographic relationships throughout southern Arizona implies that the factors that are controlling erosion and deposition in fluvial systems are regional in scope. Whether fluvial systems aggrade or degrade is a function of sediment supply and their ability to transport sediment. Most of the area within drainage systems consists of hillslopes, where sediment is generated from weathering of bedrock and in turn is weathered in place and/or transported downslope to the stream system. If hillslopes are stable, then weathering dominates and sediment supply to streams is relatively low. These conditions probably existed in this region during glacial intervals, when vegetation density on hillslopes was greater due to increased annual precipitation and/or decreased summer temperatures in this region. Hillslopes have probably been unstable during changes between glacial and interglacial conditions, as vegetation responded to changing climate and the character of precipitation and runoff varied in response to changes in the nature and frequency of thunderstorm activity. As a result of these climate-induced changes, large fluxes of sediment may have been introduced into the fluvial systems, causing periods of aggradation on the piedmont. The fans and terraces of the Madera Canyon likely record climate changes of this kind.

Geologic Hazards

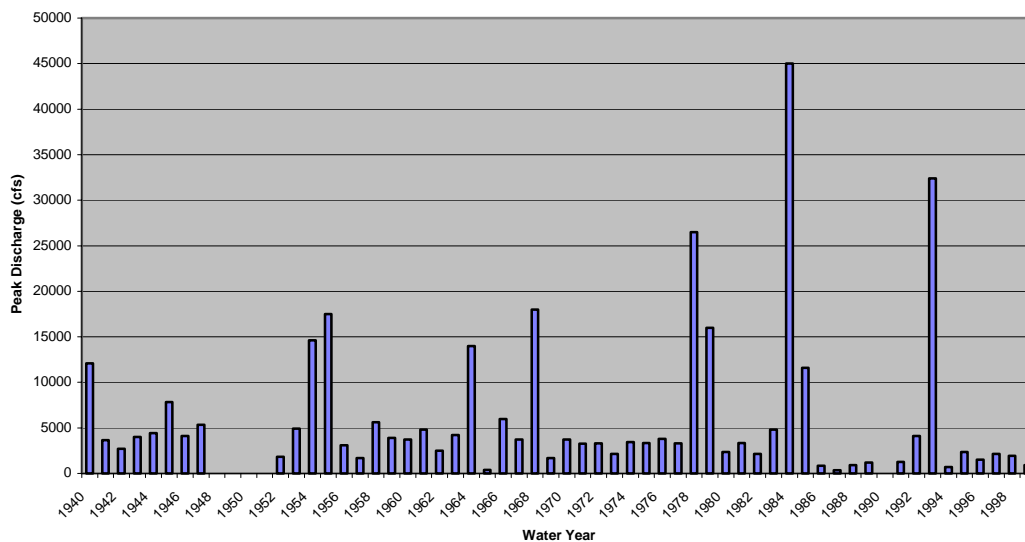
This section summarizes the character and distribution of the principal geologic hazards that exist in and around the Tucson Mountains. This information is fairly general in nature. Detailed site-specific geologic, engineering, hydrologic, or soils investigations may be required to thoroughly assess potential hazards at particular locations. More specific information on soil properties may be obtained from the USDA Natural Resources Conservation Service, and information on mapped floodplain and flood-prone areas may be obtained from the Pima County Flood Control District (unincorporated areas) and the Town of Sahuarita.

Flood hazards. Hazards related to flooding in the Green Valley - Sahuarita area may be subdivided into two broad categories. Along the Santa Cruz River, flood hazards consist mainly of channel and floodplain inundation and lateral erosion of unprotected channel banks. The most widespread flood hazards in the map area are those associated with smaller tributary drainages on piedmonts, where the extent of flood-prone area varies with the size of the stream and local topographic confinement of floodwater. This latter category of flood hazard is particularly difficult to assess in areas where channel networks are distributary and topographic relief is low. These areas may be subject to alluvial fan flooding.

The largest floods on the Santa Cruz drainages have resulted from regional storms in the winter and late summer - early fall, although summer storms have generated fairly large flows as well. Large floods in the historical record on the Santa Cruz River occurred in 1914, 1916, 1977, 1978, 1983, and 1993. At the Santa Cruz River gage near the village of Continental, the 45,000 cubic feet per second (cfs) discharge in October, 1983 is the peak of record (Figure 2; Pope and others, 1998). Other large floods occurred in January, 1993 (32,400 cfs) and October, 1977 (26,500 cfs). The channel of the Santa Cruz entrenched one to several meters below the historical floodplain in most places. The channel capacity is not large enough to convey large flood discharges through this area, however, and floodplain inundation has occurred in the larger historical floods. Lateral bank erosion has been a significant hazard during, with hundreds of feet of erosion occurring during several floods (Parker, 1995; Wood and others, 1999). The banks of some short reaches of the Santa Cruz River have been stabilized with soil cement, but the potential for serious bank erosion exists along extensive, unprotected banks formed in weakly consolidated Qyr deposits.

Smaller tributaries that drain the mountain ranges and the piedmonts are subject to flash floods. Floods on these drainages result from intense, localized thunderstorms that occur during the summer or early autumn, and stream stages typically rise and fall rapidly during floods. Flood hazards are relatively easy to manage where topographic relief contains floodwater to channels and adjacent low terraces. In these situations, the area that may be impacted by flooding is restricted and should be easy to avoid. It is much more difficult to assess and manage flood hazards associated with alluvial fan flooding. This type of flooding occurs where topographic relief is minimal and floodwater can spread widely. In these areas, channels may or may not be well defined, and their

Santa Cruz River Gage at Continental



Santa Cruz River Gage at Tucson

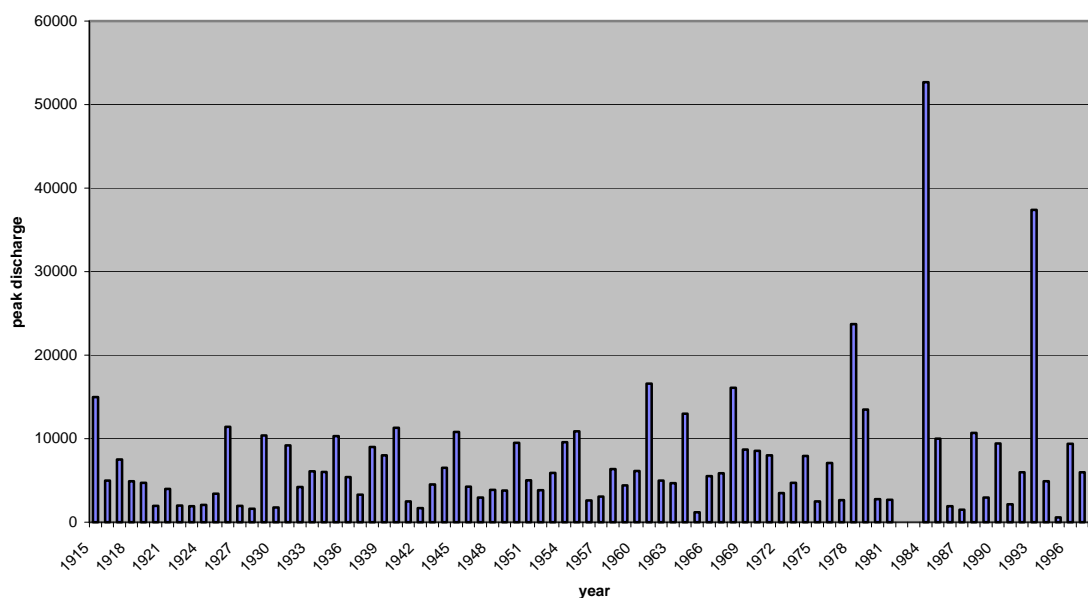


Figure 2. Annual peak discharge estimates for the Santa Cruz River at Continental (in the map area) and downstream at Tucson, where the record is longer (U.S. Geological Survey, 2000).

positions may shift during floods, and inundation is likely to be widespread during floods.

Surficial geologic mapping provides important information about the extent of flood-prone areas on the piedmonts, and it is the best way to delineate areas that may be prone to alluvial fan flooding. Floods leave behind physical evidence of their occurrence in the form of deposits. Therefore, the extent of young deposits on piedmonts is a good indicator of areas that have been flooded in the past few thousand years. These are the areas that are most likely to experience flooding in the future. Following this logic, the extent of potentially flood-prone areas on the piedmont varies with the extent of young deposits (units Qy₂, Qy₁, Qy, and possibly Qly). Active alluvial fans may be recognized by both distributary (downstream-branching) channel networks and laterally extensive young deposits between channels (see Pearthree and others, 1992).

Most of the modern drainages on the Sierrita piedmont have tributary networks that are topographically confined by ridges of older alluvium. Along these drainages, flood hazards are restricted to active channels and adjacent low, young terraces (unit Qy₂). Portions of the slightly older and higher terraces that are mapped as unit Qy₁ may be subject to rare inundation in extreme floods. Lateral channel bank erosion may occur in young, weakly consolidated deposits. A few distributary drainage systems exist on the Sierrita piedmont, but channels are generally entrenched into much older deposits and thus these systems are not active alluvial fans. Unconfined flow during floods occurs along both the western and eastern margins of the Santa Cruz floodplain, where tributaries debouch from the topographically confined foothills onto the Qyr terrace. On the Santa Rita piedmont, drainages in the upper piedmont are topographically confined and flood hazards are of limited extent. In the southern part of the map area (the southern part of the Green Valley quadrangle), drainages are topographically confined to very near the Santa Cruz floodplain. Farther north, however, most drainages have unconfined middle piedmont reaches that are subject to broad sheetflooding and possibly alluvial-fan flooding. Flood hazards are greatest at the upslope end of these areas, at the transition from confined to unconfined flow, because of fairly deep flow, high flow velocities, and the potential for significant changes in channel position during floods.

Soil problems. Soils in the Tucson area present a number of problems to homeowners. Cracking of foundations, walls, driveways and swimming pools causes headaches and costs millions of dollars each year in repairs. Severe or recurring damage can lower the value of a house or commercial property. Leading in the list of potential soil properties that can cause structural failures are expansive soils and collapsing soils. Properties of problem soils are generally related to the type and amount of clay, and to the conditions under which the clay originated. Clay minerals can form in-place by weathering of rocks, or by deposition from water or wind.

Potential soil problems in middle and upper piedmont areas consist of shrink-swell potential, low infiltration rates, and hard substrate. Shrink-swell problems may exist on clay-rich soils of unit Qm and Qo, although the gravel that is common in these deposits likely decreases the severity of unstable soil problems. Excavation may be difficult and near-surface infiltration rates low on the oldest piedmont units (Qo, and QTs) due to the existence of carbonate- and silica-cemented hardpans (petrocalcic and duric horizons).

Excavation and infiltration problems may be encountered on all surficial units in the uppermost piedmont areas because of the existence of bedrock at shallow depths.

Land subsidence and earth fissures. In the Tucson area, agricultural development and population increases have resulted in the heavy use of groundwater resources. Because groundwater recharge in the area is limited, groundwater levels have been lowered by up several hundred feet in parts of the Tucson area. Earth fissures have developed in Avra Valley, and recent measurements have indicated that the surface of the central part of the Tucson basin (north of the map area) has begun to subside.

Withdrawal of groundwater at rates faster than natural recharge leads to declines in water tables. Water levels in parts of Tucson's central well field had declined by more than 150 feet by 1981 (Anderson, 1988) and are continuing to decline. Dewatering of sediments causes compaction, which in turn results in lowering of the land surface. In every Arizona groundwater basin where major groundwater overdraft has occurred, subsidence has followed. The land surface has subsided as much as 15.4 feet near Eloy (Slaff, 1993) and 18 feet west of Phoenix (Schumann, 1992).

In the Tucson basin, subsidence was detected in re-leveling surveys in 1952 (Platt, 1963), but maximum total subsidence was only about 0.5 feet by 1980 (Anderson, 1988). Recent surveys have indicated continuing subsidence as water levels decline under Tucson. Hatch (1991) measured an average subsidence rate of 1 cm per year over the Tucson basin from 1987 to 1991. Measurements in the Tucson basin suggested that the rate of subsidence had increased markedly since 1980. Confirmation of the increased rate of subsidence is provided by a preliminary survey of subsidence using satellite-based synthetic aperture radar interferometry. Using SAR interferometry, a British company measured 9 cm of subsidence over a 3 year, 9 month period, ending in March, 1997, yielding a rate of 2.4 cm/yr (Ren Capes, NPA Group, personal communication).

The Tucson basin is the only one of Arizona's deep groundwater basins where groundwater level declines and land subsidence have not yet been followed by earth fissures, probably because the amount of total subsidence has thus far been relatively small compared to other basins. Based on the amount and rate of past subsidence, parts of the Tucson basin can expect subsidence of more than 10 feet by the year 2030 (Anderson, 1988). With the expected lowering of water tables and subsequent predicted land subsidence, earth fissures will most certainly develop in Tucson as they have elsewhere. Anderson (1988) identified several zones where land subsidence potential is likely to occur if groundwater depletion continues at current rates. Within the project map area, the zones of potential subsidence parallel the Santa Cruz River through the Sahuarita area, where the potential for as much as 10 ft. (3 m) of subsidence by the year 2030 was recognized (Anderson, 1988, sheet 3). There is potential for severe localized differential subsidence along the margins of the zone of maximum projected subsidence.

Earthquake hazards. The surficial geology of the Santa Rita piedmont provides information that has been used to evaluate the behavior of the Santa Rita fault zone, which extends along the Santa Rita Mountains for about 35 miles (60 km) from Tubac to Corona de Tucson (Pearthree and Calvo, 1987). Along the fault zone, a discontinuous zone of fault scarps offset Pleistocene alluvium. Scarps trend northeast to north-south and are 1 to 6 km west of the base of the Santa Rita Mountains. Scarps range up to about 5 m

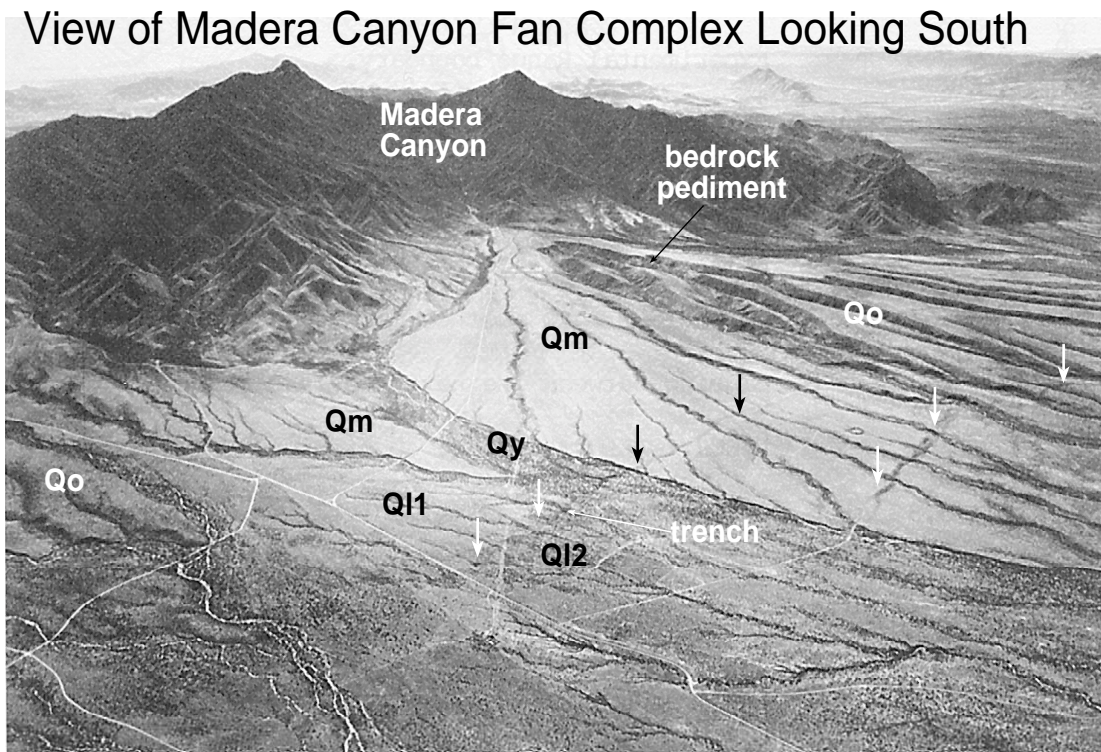


Figure 3. Aerial view of the Madera Canyon fan area showing alluvial surfaces of different ages and the scarps of the Santa Rita fault zone. Fault scarps exist on Qo, Qm, and Ql₁ surfaces; Qy and Ql₂ surfaces are not faulted. Note the tremendous difference in dissection between the upper parts of the Qo and Qm surfaces, even though both surfaces have strongly developed, red, clay-rich soils implying great antiquity. The fault zone makes a sizable right step on the Qm surface. The surface expression of Quaternary faulting dies out near the left edge of the photo, but scarps pick up again farther north and continue to beyond the northern end of the Santa Rita Mountains. The fault trench (Figure 4) was excavated in a wash incised into the Ql₁ surface. Aerial photograph is courtesy of Peter Kresan.

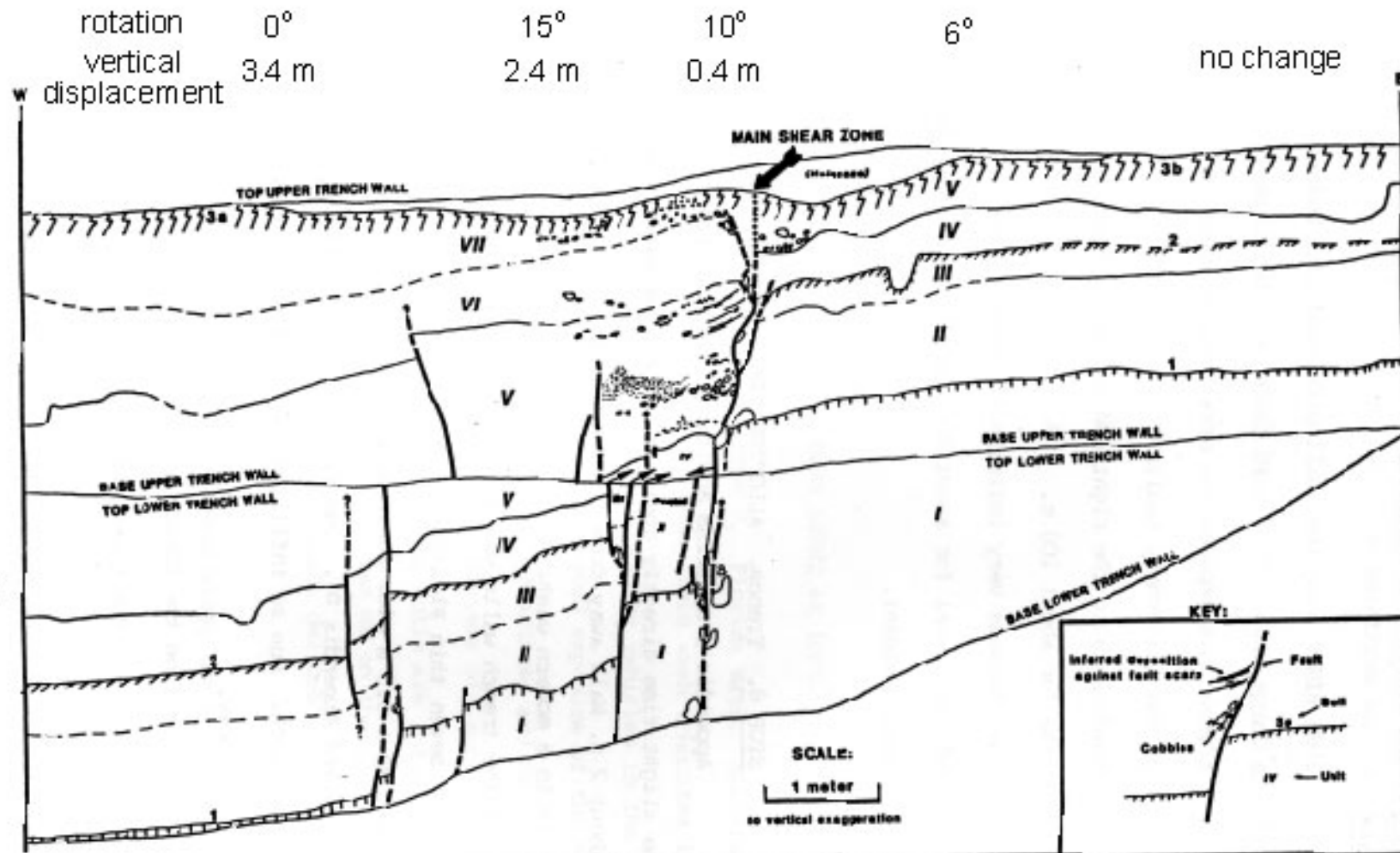


Figure 4. Stratigraphy and faults exposed in a trench excavated across the Santa Rita fault zone in the Madera Canyon area in 1980. Units I through IV are vertically displaced a total of 3.4 m across 3 faults. The top of unit V is displaced only 2.2 m, and its thickness is much greater on the downthrown block, which was interpreted to indicate that unit V deposition partially buried an existing fault scarp. Unit V was subsequently displaced in the youngest faulting event. This figure is modified from Pearthree and Calvo (1987).

in height and have maximum slope angles up to about 10°. Surficial deposits as young as late Pleistocene (unit Ql₁) are displaced, but latest Pleistocene (unit Ql₂) and Holocene (unit Qy) deposits are not faulted, which brackets the age of youngest faulting between 10-20 ka and 75-130 ka. Quantitative analysis of fault scarp morphologies indicates that the youngest surface rupture occurred between about 60-100 ka. Fault displacement of late Pleistocene surfaces averages about 2 m, in contrast to 4 to 5 m of displacement of middle and early Pleistocene surfaces (units Qm and Qo). Displacement of middle and early Pleistocene surfaces is similar. These relationships imply that the fault zone was not active during the early Pleistocene between the deposition of unit Qo and unit Qm.

Detailed analysis of a trench excavated across the fault zone corroborated the assessment of fault behavior outlined above. Middle Pleistocene units, including a well-developed buried soil, have been displaced 3.4 m across several individual fault strands in the trench (Figure 4; Pearthree and Calvo, 1987). Displacement occurred as a result of both fault displacement and westward rotation, including some rotation of strata near the fault zone in the footwall. A late Pleistocene unit (unit V) thickens across the fault zone, implying that it was deposited across an existing fault scarp. The top of unit V is displaced 2.2 m, which has been interpreted as the displacement in the youngest faulting event (Pearthree and Calvo, 1987). Thus, at the trench site, there have been two surface faulting events in the past several hundred thousand years with 1.2 and 2.2 m of vertical displacement. Using fault displacement estimates and various estimates of surface rupture length, Pearthree and Calvo (1987) concluded that two paleoearthquakes of magnitude 6 $\frac{3}{4}$ to 7 $\frac{1}{4}$ occurred along the Santa Rita fault zone in the past 200 to 300 ka. Geophysical investigations on the northern part of the fault zone indicate that that part of the fault dips shallowly to the northwest (Johnson and Loy, 1992). This implies that the area of the seismogenic fault may be larger than previously suspected, and that it dips beneath the Tucson metropolitan area.

The evidence of low frequency Quaternary fault activity combined with the existence of broad bedrock pediments on the west side of the Santa Rita Mountains indicates that the long-term slip rate on the Santa Rita fault zone is very low. The very long recurrence intervals between surface ruptures and evidence for very low long-term slip rates are consistent with other Quaternary fault zones that have been studied in southeastern Arizona, southwestern New Mexico, and northern Sonora (Pearthree, 1986; Bull and Pearthree, 1988; Demsey and Pearthree, 1994; Pearthree, 1998). The fault activity that is observed in this region is either a late pulse of activity related to the Basin and Range disturbance or a new, weakly extensional tectonic regime that has developed in the middle to late Quaternary.

References

- Anderson, S.R., 1988, Potential for aquifer compaction, land subsidence, and earth fissures in the Tucson basin, Pima County, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA-713, 3 sheets, scale 1:250,000.
- Betancourt, J.L., 1990, Tucson's Santa Cruz River and the arroyo legacy: unpublished Ph.D. dissertation, University of Arizona, 239 p.
- Bull, W.B., and Pearthree, P.A., 1988, Frequency and size of Quaternary surface ruptures on the Pitaycachi fault, northeastern Sonora, Mexico: Bull. Seis. Soc. Amer., v. 78, p. 956-978.
- Bull, W.B., 1991, Geomorphic Response to Climatic Change, New York: Oxford University Press, 326 p.
- Cooper, J.R., 1973, Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona; U.S. Geological Survey Miscellaneous Geologic Investigations Map I-745, 1 sheet, scale 1:48,000.
- Demsey, K.A., House, P.K., and Pearthree, P.A., 1993, Detailed surficial geologic map of the southern piedmont of the Tortolita Mountains, Pima County, southern Arizona: Arizona Geological Survey Open-File Report 93-14, 8 p. scale 1:24,000.
- Demsey, K.A., and Pearthree, P.A., 1994, Surficial and environmental geology of the Sierra Vista area, Cochise County, Arizona: AZGS OFR 94-6, 14 p., scale 1:24,000.
- Drewes, Harald, 1971, Geologic map of the Sahuarita quadrangle, southeast of Tucson, Pima County, Arizona: U.S. Geological Survey Misc. Geologic Invest. Map I-613, scale 1:48,000.
- Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the basin and range area of southern New Mexico -- guidebook of the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.
- Hatch, M.A., 1991, Global positioning system measurement of subsidence in the Tucson Basin, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 87 p.
- Helmick, W.R., 1986, The Santa Cruz River terraces near Tubac, Santa Cruz County, Arizona: University of Arizona unpublished M.S. thesis, 96 p., scale 1:19,800.
- Jackson, G.W., 1989, Surficial geologic maps of the northeastern, southeastern, and southwestern portions of the tucson metropolitan area: Arizona Geological Survey Open-File Report 89-2, 6 p., 7 sheets, scale 1:24,000.
- Jackson, G.W., 1990, Quaternary geologic map of the Corona de Tucson 7.5' quadrangle, Arizona: Arizona Geological Survey Open-File Report 90-3, 6 p., scale 1:24,000.
- Johnson, R.A., and Loy, K.L., 1992, Seismic reflection evidence of seismogenic low-angle faulting in southeastern Arizona: Geology, v. 20, n. 7, p. 597-600.
- Klawon, J.E., Dickinson, W.R., and Pearthree, P.A., 1999, Surficial geology and geologic hazards of the northern Tucson basin, Tucson North and Sabino Canyon 7 1/2'

- quadrangles: Arizona Geological Survey Open-File Report 99-21, 21 p. 1 sheet, scale 1:24,000.
- Machette, M.N., 1985, Calcic soils of the southwestern United States: in Weide, D.L., ed., *Soils and Quaternary Geology of the Southwestern United States*: Geological Society of America Special Paper 203, p. 1-21.
- McKittrick, M.A., 1988, Surficial geologic maps of the Tucson metropolitan area: Arizona Geological Survey Open-File Report 88-18, 7 p., 12 sheets, scale 1:24,000.
- Menges, C.M., and McFadden, L.D., 1981, Evidence for a latest Miocene to Pliocene transition from Basin-Range tectonic to post-tectonic landscape evolution in southeastern Arizona: Arizona Geological Society Digest 13, p. 151-160.
- Menges, C.M., and Pearthree, P.A., 1989, Late Cenozoic tectonism and landscape evolution in Arizona, in Jenney, J., and Reynolds, S.J., eds., *Geologic Evolution of Arizona*: Arizona Geological Society Digest 17, p. 649-680.
- Parker, J.T.C., 1995, Channel change on the Santa Cruz River, Pima County, Arizona: U.S. Geological Survey Water-Supply Paper 2429, 58 p.
- Pearthree, P.A., 1986, Late Quaternary faulting and seismic hazard in southeastern Arizona: Arizona Geological Survey Open-File Report 86-8, 22 p.
- Pearthree, P.A., 1998, Quaternary fault data and map for Arizona: Arizona Geological Survey Open-File Report 98-24, 122 p., map scale 1:750,000.
- Pearthree, P.A., and Biggs, T.H., 1999, Surficial geology and geologic hazards of the Tucson Mountains: Arizona Geological Survey Open-File Report 99-22, 12 p., 2 sheets, scale 1:24,000.
- Pearthree, P.A., and Calvo, S.S., 1987, The Santa Rita fault zone: Evidence for large magnitude earthquakes with very long recurrence intervals, Basin and Range province of southeastern Arizona: *Bull. Seis. Soc. Amer.*, v. 77, p. 97-116.
- Pearthree, P.A., Demsey, K.A., Onken, Jill, Vincent, K.R., and House, P.K., 1992, Geomorphic assessment of flood-prone areas on the southern piedmont of the Tortolita Mountains, Pima County, Arizona: Arizona Geological Survey Open-File Report 91-11, 31 p., scale 1:12,000 and 1:24,000, 4 sheets.
- Pearthree, P.A., Ferguson, C.A., Gilbert, W.G., and Skotnicki, S.J., 2000, Geologic map and geologic hazards of the Three Points quadrangle, Pima County, Arizona: Arizona Geological Survey Open-File Report 00-12, 19 p., map scale 1:24,000.
- Platt, W.S., 1963, land-surface subsidence in the Tucson area: University of Arizona unpublished Masters Thesis, Department of Geology, 38 p.
- Pope, G.L., Rigas, P.D., and Smith, C.F., 1998, Statistical summaries of streamflow data and characteristics of drainage basins for selected streamflow-gaging stations in Arizona through Water Year 1996: U.S. Geological Survey Water-Resources Investigations Report 98-4225, 907 p.
- Schumann, H.H., 1992, Land subsidence and earth-fissure hazards near Luke Air Force Base, Arizona, in U.S. Geological Survey Subsidence Interest Group conference,

- Edwards Air Force Base, Antelope Valley, California, November 18-19, 1992 - Abstracts and Summary: US Geological Survey Open-File Report 94-532, p. 18-21.
- Sellers, W.D., and Hill, R.H., 1974, Arizona Climate, 1931-1972: Tucson, University of Arizona Press, 616 p.
- Sellers, W.D., and Hill, R.H., 1974, Arizona Climate, 1931-1972: Tucson, University of Arizona Press, 616 p.
- Shafiquallah, M., Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 201-260.
- Slaff, Steve, 1993, Land subsidence and earth fissures in Arizona, Arizona Geological Survey Down-to-Earth Series 3, 24 p.
- U.S. Geological Survey, 2000, Real-time data for selected stream gaging sites in Arizona website; annual peak flow data.
- Western Regional Climate Center, 2000, Arizona climate summaries, in Western U.S. historical climate summaries, WRCC Web Page, Desert Research Institute, University of Nevada.
- Wood, M.L., House, P.K., and Pearthree, P.A., 1999, Historical geomorphology and hydrology of the Santa Cruz River: Arizona Geological Survey Open-File Report 99-13, 98 p., 1 sheet, scale 1:100,000.